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1. Your reference — 563GB

2. Patent application number *(The Patent Office will fill in this part)* — 0215557.0

3. Full name, address and postcode of the or of each applicant *(underline all surnames)* — Renishaw plc, New Mills, Wotton-under-Edge, Gloucestershire, GL12 8JR

   Patents ADP number *(if you know it)* — 2691002

   If the applicant is a corporate body, give the country/state of its incorporation — United Kingdom

4. Title of the invention — Laser Calibration Apparatus

5. Name of your agent *(if you have one)* — J T Jackson et al

   "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)* — Renishaw plc, Patent Department, New Mills, Wotton-under-Edge, Gloucestershire, GL12 8JR

   Patents ADP number *(if you know it)* — 6446291002

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
-	-	-

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application	Date of filing *(day / month / year)*
-	-

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:*
   a) any applicant named in part 3 is not an inventor, or
   b) there is an inventor who is not named as an applicant, or
   c) any named applicant is a corporate body.
   See note (d)) — Yes

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Description	12
Claim(s)	0
Abstract	0
Drawing(s)	6

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Priority documents	0
Translations of priority documents	0
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	0
Request for preliminary examination and search *(Patents Form 9/77)*	0
Request for substantive examination *(Patents Form 10/77)*	0
Any other documents *(please specify)*	0

11. I/We request the grant of a patent on the basis of this application.

Signature Date 05.07.2002

AGENT FOR THE APPLICANT

12. Name and daytime telephone number of person to contact in the United Kingdom A Iles 01453 524524

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LASER CALIBRATION APPARATUS

The present invention relates to optical apparatus for measuring deviations of a trajectory from a straight line. More particularly, the invention relates to optical apparatus for measuring deviations of a trajectory from a straight line in the movement of a first machine component relative to a second machine component. The machine components may be parts of a coordinate positioning apparatus which may comprise, for example, a machine tool or a coordinate measuring machine.

Deviations in the movement of a machine component as it moves along a trajectory generally involve rotation of the component about one or more axes of the machine, usually referred to as the X, Y and Z axes, and are referred to as pitch, roll and yaw errors. There are also errors in straightness of the movement which involve lateral deviations of the machine component from the main movement axis.

The present invention provides apparatus for measuring deviation of a trajectory from a straight line in the movement of a first body with respect to a second body comprising:

a transmitter unit mounted on one of the first and second bodies;

an optic unit mounted on the other of the first and second bodies;

wherein the transmitter unit directs a plurality of light beams towards the optic unit such that two or more light beams are received within the optic unit;

wherein one of the transmitter unit and the optic

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unit is provided with two or more detectors to detect the light beams transmitted to or reflected from the optic unit;

and wherein the position of the light beams on the detectors is used to calculate the deviation of a trajectory from a straight line of one of the first and second bodies with respect to the other of the first and second bodies in at least one degree of freedom.

Preferably the position of the returning light beams on the detectors is used to calculate the deviation of a trajectory from a straight line of one the first and second bodies with respect to the other of the first and second bodies in five degrees of freedom.

Preferably the five degrees of freedom are pitch, yaw, roll and straightness along two axes perpendicular to the axis of movement of the first or second body.

Preferably the plurality of light beams directed towards the optic unit are substantially parallel.

Preferably the optic unit is provided with two or more optical elements each to reflect the respective two or more light beams towards the transmitter unit; and wherein the transmitter unit is provided with the two or more detectors to detect the light beams reflected from the optic unit

In a preferred embodiment, the optic unit is provided with three optical elements each to reflect three respective light beams towards the transmitter unit; and wherein the transmitter unit is provided with three detectors to detect the three light beams reflected

from the optic unit.

Preferably the optical elements in the optic unit comprise retroreflectors. Two of the retroreflectors are positioned side-by-side in the optic unit and the third retroreflector is positioned behind one of the first and second retroreflectors. Preferably the third retroreflector is conceptually behind one of the first and second retroreflectors. A mirror may be provided to fold the light beam directed to the third retroreflector in order to place the third retroreflector in a more convenient position.

Preferably the detectors comprise two-dimensional arrays of pixels. The detectors may comprise, for example, CMOS sensors, charge-coupled devices (CCDs) or charge-injection devices (CID).

Preferably the optic unit is mounted on a movable body. The optic unit preferably has no trailing leads which could cause unwanted movement and affect the accuracy.

Preferably the light beams are transmitted from at least one coherent light source, wherein the light beams are intensity modulated to reduce their coherence length.

The light beams are intensity modulated to cause frequency variation which reduces the coherence pattern of the detected beams.

Preferably the light beams are intensity modulated by turning the at least one light source on and off.

Preferably the apparatus also includes linear displacement measuring apparatus, such as an interferometer. This may comprise a light source in the transmitter unit to produce a light beam which is directed to the optic unit, a retroreflector in the optic unit to reflect the light beam towards the transmitter unit, and a fourth detector in the transmitter unit to detect the returning light beam.

Embodiments of the invention will now be described by way of example and with reference to the accompanying drawings in which:

Fig 1 is a schematic representation of the measuring device mounted on a coordinate measuring machine;

Fig 2 is a plan view of the optical components in the transmitter unit and the optic unit;

Fig 3 is a perspective view of the optical components in both the transmitter unit and the optic unit;

Fig 4 is a plan view of a linear displacement measuring device in the transmitter unit and the optic unit;

Fig 5 is a plan view of a first alternative arrangement of the retroreflectors in the optic unit;

Fig 6 is a plan view of a second alternative arrangement of the retroreflectors in the optic unit; and

Fig 7 is a plan view of transmitter unit and the optic unit according to a second embodiment of the invention.

Fig 1 shows the calibration apparatus mounted on a coordinate measuring machine (CMM). A transmitter unit

10 is mounted on the machine table 14 of the CMM. As described in our International Patent Application WO02/04890 the base 18 of the transmitter unit 10 and a base unit 20 mounted on the machine table 14 are provided with complementary parts of a kinematic support 22 which enable the transmitter unit 10 to be accurately aligned along any of the X,Y,Z,-X and -Y axes of the CMM or along any other desired direction. An optic unit 12 is mounted on the quill 16 of the CMM. As also described in International Patent Application No. WO02/04890, the transmitter unit 10 and the optic unit 12 have complementary parts of a kinematic support 24A, 24B such that when they are brought into contact with each other, they become accurately aligned with one another.

The transmitter unit 10 is thus mounted on the machine table 14 and aligned with one of the X,Y,Z,-X or -Y axes of the machine or any other desired direction. The optic unit 12 is aligned with the transmitter unit 10 and is mounted on the quill 16 of the machine. The optic unit 12 and quill 16 are moved along a path in the direction to which the transmitter unit 10 is aligned. The apparatus may then be used to measure the distance of the optic unit 12 from the transmitter unit 10 and to measure deviations in the movement of the optic unit 12 during its movement along this path.

Figs 2-4 show the arrangements of the optical elements within the transmitter unit 10 and the optic unit 12. A first group of optical elements 26-40 are used as a linear displacement measuring device, for example an interferometer, to measure the distance of the optic unit from the transmitter unit. These are omitted from

Figs 2 and 3 for clarity but are shown separately in Fig 4. Although one particular type of interferometer will be described this may be replaced by any other suitable type of linear displacement measuring apparatus. The interferometer apparatus comprises a light source 26 in the transmitter unit 10 which produces a light beam 28. A beam splitter 30 splits the beam 28 and sends a first beam 32 towards a first retroreflector 36 in the optic unit 12 and a second beam 34 towards a second retroreflector 38 in the transmitter unit 10. Both beams 32,34 are reflected by their respective retroreflectors 36, 38 back to the beamsplitter 30 and on to the detection unit 40. This interferometer is described in more detail in European patent EP 0668483.

Referring to Figs 2 and 3, three light sources 42A,42B,42C project three parallel light beams 44,46,48 from the transmitter unit 10 to the optic unit 12. The three light sources may comprise, for example, three optical fibre ends in a known manner. Alternatively a single light source may be used which produces three parallel light beams by using optics such as beams splitters and mirrors.

The optic unit 12 is provided with three spaced retroreflectors 62,64,66. The retroreflectors 62,64,66 reflect the beams 44,46,48 back towards three detectors 68,70,72 located within the transmitter unit 10. These detectors 68,70,72 may comprise CMOS sensors which comprise two-dimensional arrays of pixels allowing the position of a light beam on the detector to be measured. Alternatively a charge-coupled device (CCD) may also be used in place of the CMOS sensor.

Other detectors allowing the position of the light beam to be determined may also be used, for example, charge-injection devices (CID), quad cell photodiodes or positional signal detectors. In particular positional signal detectors, which use the voltage difference between opposite sides of the detector to indicates the position of the incident light beam, may be turned to work at a particular frequency and may thus be tuned to eliminate room lighting effects by tuning it to a higher or lower frequency than the room lighting.

As the optic unit 12 moves along its path, the positions of the returning light beams 44,46,48 on the detectors 68,70,72 will change, due to deviations in the movement of the optic unit 12 from this path. The use of three retroreflectors 62,64,66 with images laterally displaced with respect to each other enables two straightnesses and pitch, roll and yaw to be deduced of the optic unit.

In this example, the motion of the optic unit is along the X axis of the machine, as illustrated in Fig 2. Retroreflectors 62 and 64 are located in the optic unit 12 spaced in the Y direction. The straightness of the axis of motion (X axis) of the optic unit is half the mean displacement of the change in position of the light beams 44,46 on detectors 68,70 in the direction of the axes perpendicular to the directions of motion (i.e. Y and Z axes in this case). If, as described below, the detectors are located in the optic unit 12 then the straightness of the axis of motion of the optic unit is the mean displacement of the change in position of the light beams 44,46 on the detectors 68,70 in the direction of the axes perpendicular to the

directions of motion.

If the three light beams 44,46,48 directed towards the optic unit 12 are not parallel, a correction must be applied to the detector outputs to correct for this error. If the beams 44,46,48 are mis-aligned, the measurement is corrected from calibration of the two units 10,12.

The roll of the optic unit 12 is measured by the differential displacement in the Z direction between these same two beams 44,46 on their respective detectors 68,70.

The third retroreflector 66 enables the pitch and yaw of the optic unit 12 to be measured. This third retroreflector 66 is placed conceptually behind one of the first and second retroreflectors 62,64 in the optic unit 12. In this example, the third retroreflector 66 is placed vertically above the first or second retroreflector. This is achieved by vertically displacing one of the output beams 48 from the transmitter unit 10 and placing a mirror 54 above one of the retroreflectors 62 to direct the beam 48 towards the retroreflector 66 placed above the other retroreflector 64. Pitch and yaw are measured by the differential displacement on detectors 68,72 between the two beams 44,48 in the Z and X directions respectively.

Alternatively, the third retroreflector may be actually located behind the second retroreflector. Fig 5 shows such an arrangement in which a large third 166 retroreflector is positioned behind a small second

retroreflector 162. The outgoing light beams 144, 148 are arranged such that the beam 148 directed towards the large third retroreflector 166 is not intercepted by the small second retroreflector 162. However this arrangement has the disadvantage that it adds extra volume to the optic unit 12.

Another arrangement of the second and third retroreflectors is shown in Fig 6 in which the third retroreflector 266 is located behind the second retroreflector 262. The second reflector 262 has a beam splitter surface 261 and prisms 263 located on its rear surface to allow some light to pass through it to the third retroreflector 266 whilst reflecting some light itself. This arrangement has the disadvantage that it is relatively expensive, adds volume to the optic unit and some light 265 is lost perpendicular to the outgoing and incoming beams.

The first arrangement shown in Figs 2 and 3 in which the third retroreflector is conceptually behind the second retroreflector introduces cross coupling to the system as the light beams directed to the second and third retroreflectors are angled to one another. This arrangement is advantageous as it is a more compact design, saving volume in the optic unit.

In order to accurately determine the centre of the optical beams 44,46,48 on their respective detectors 68,70,72, the beams are required to have minimal stray reflection components. However in practice it is difficult to remove the interference patterns caused by the collimating lenses and retroreflectors. To reduce these effects an incoherent light source is required,

however it is difficult to collimate an incoherent light source to the required level of this apparatus. This problem is solved by using a coherent light source which is intensity modulated over time to cause frequency variation. The relevant time interval for the intensity modulation is the exposure time for a given pixel in the detector.

There is a minimum exposure time for a given pixel in the detector. For example, if the exposure time for a given pixel is 10μs and the intensity is measured to an accuracy of within 1%, then without locking the exposure time to the intensity modulation signal, the light source may be modulated to greater than 10MHz to have the desired effect.

The coherent light source may be intensity modulated by other means. For example, the light may be passed through an optical fibre which is wound around a piezoelectric material. Pulsing the piezoelectric material causes its diameter to change, resulting in variation in the optical length of the optical fibre and hence modulation of the light beam thus reducing its coherence length.

Room lighting has been found to have an effect on the detection of the beam centres incident on the detectors. In order to remove this effect the image capture period of the detectors needs to be synchronised to the room lighting, i.e. to mains frequency. In addition, to remove the effect of room lighting two images are required, one with the return beam present and one without. The difference between the two images is used to calculate the centroid.

This apparatus has the advantage that all six degrees of freedom may be measured simultaneously.

Furthermore, in the preferred embodiment, the optic unit contains only optical elements i.e. retroreflectors and mirrors. This ensures that measurements are not affected by dragging cables etc, affecting the movement of the optic unit which is mounted on a moving machine component. In this apparatus the detectors and light sources to which trailing leads are associated are all located in the transmitter unit which is mounted on a fixed machine component. Where the coordinate positioning apparatus is a machine tool, the optic unit may be mounted on the spindle and the transmitter unit may be mounted on the machine bed. The machine bed is very big and heavy which results in the trailing leads on the transmitter unit having very little affect on the movement of the transmitter unit. Conversely trailing leads on the optic unit which is mounted on the spindle would affect its movement and thus the accuracy of the system.

The invention is not limited to the embodiment in which the optic unit contains only optical element. Fig 7 shows an embodiment in which the detectors 68,70,72 are located in the optic unit 12. However this embodiment has the disadvantage that both units have trailing leads (i.e. leads to the light source in the transmitter unit and to the detectors in the optic unit). These trailing leads may effect the accuracy of the system.

An advantage of the present invention is that it is not limited to taking measurements when both units are

stationary. Such a stepwise method of moving the optic unit to a new position, taking the measurement when stationary, and then repeating at a new position is not time effective. The current invention allows images to be taken whilst the optic unit is in motion.

The detectors require time to detect the image, to allow the image to be processed and a signal created. The images detected whilst the optic unit is in motion will be blurred. These images are averaged over the distance moved by the optic unit.

The resulting signals from the detectors will be noisy. This is overcome by parametrically fitting the data. For example the straightness reading s_x may be fitted to a quadratic curve, as illustrated below.

$$S_x = a + by + cz^2$$

Time-averaging is not required for the readings taken by the interferometer as this already takes readings to nanometric precision.

Although in a preferred embodiment three detectors and three parallel beams are required to detect deviations in all five degrees of freedom, only two detectors and two parallel beams are required in the apparatus to detect deviations in any one degree of freedom.

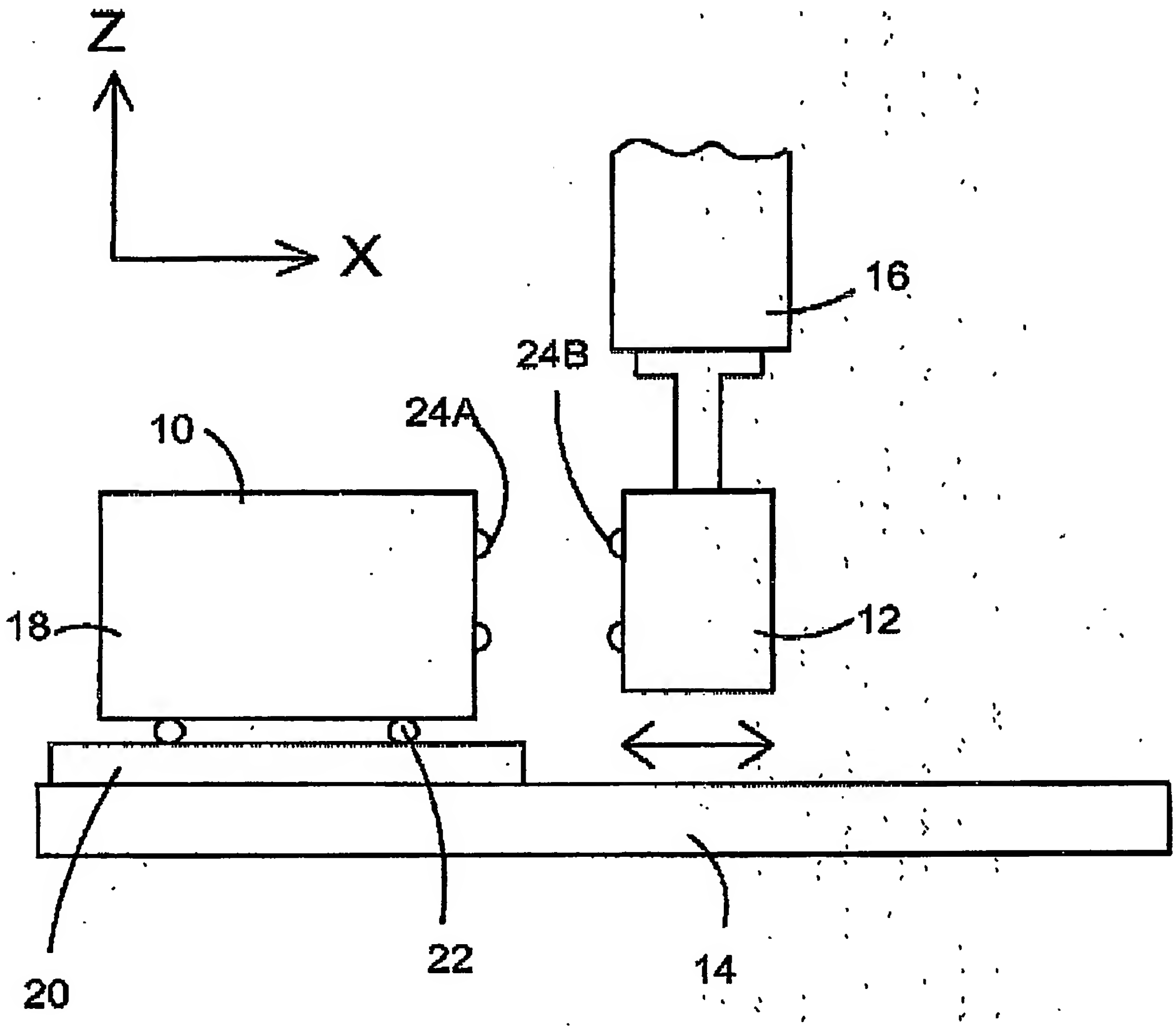

Fig 1

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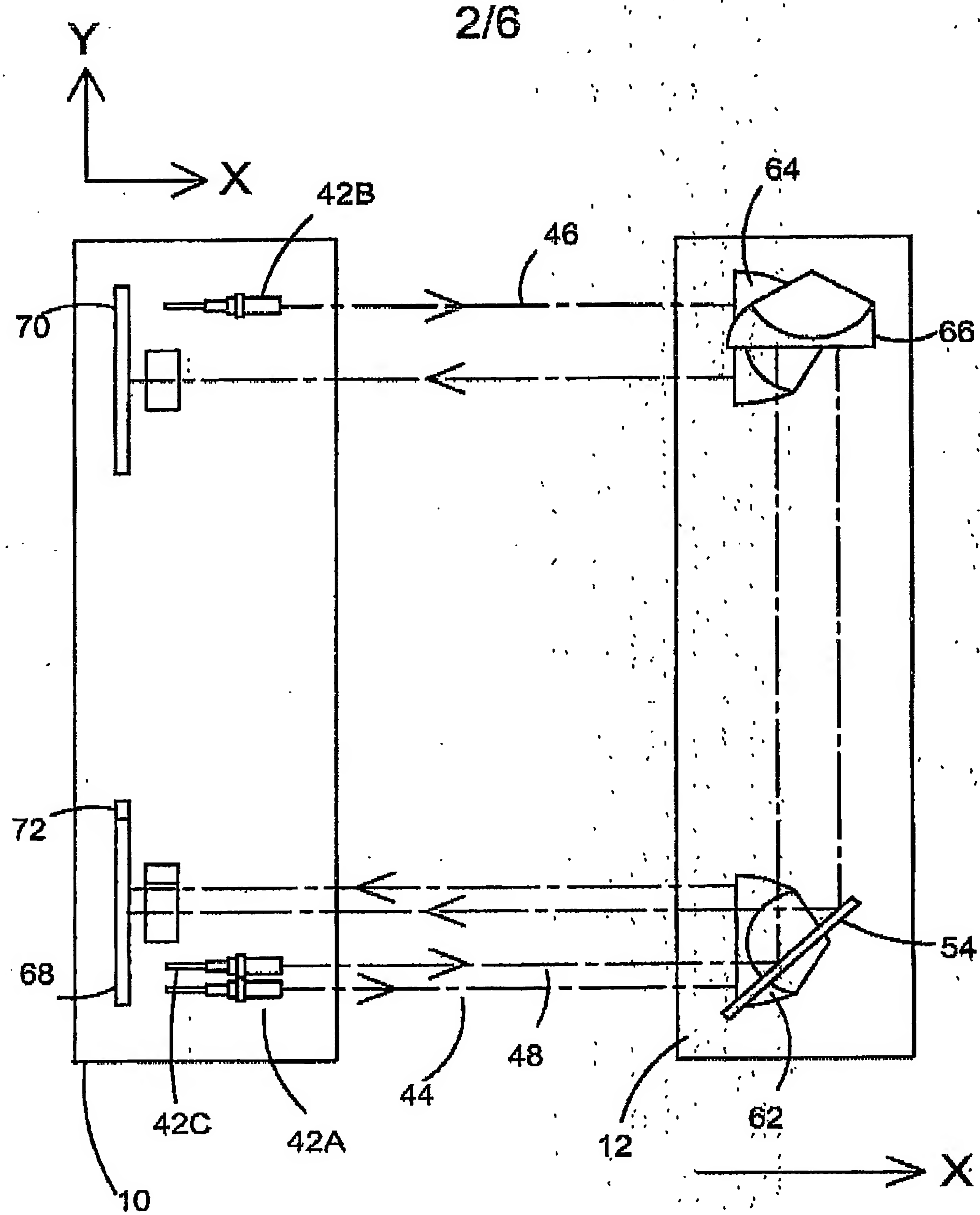

Fig 2

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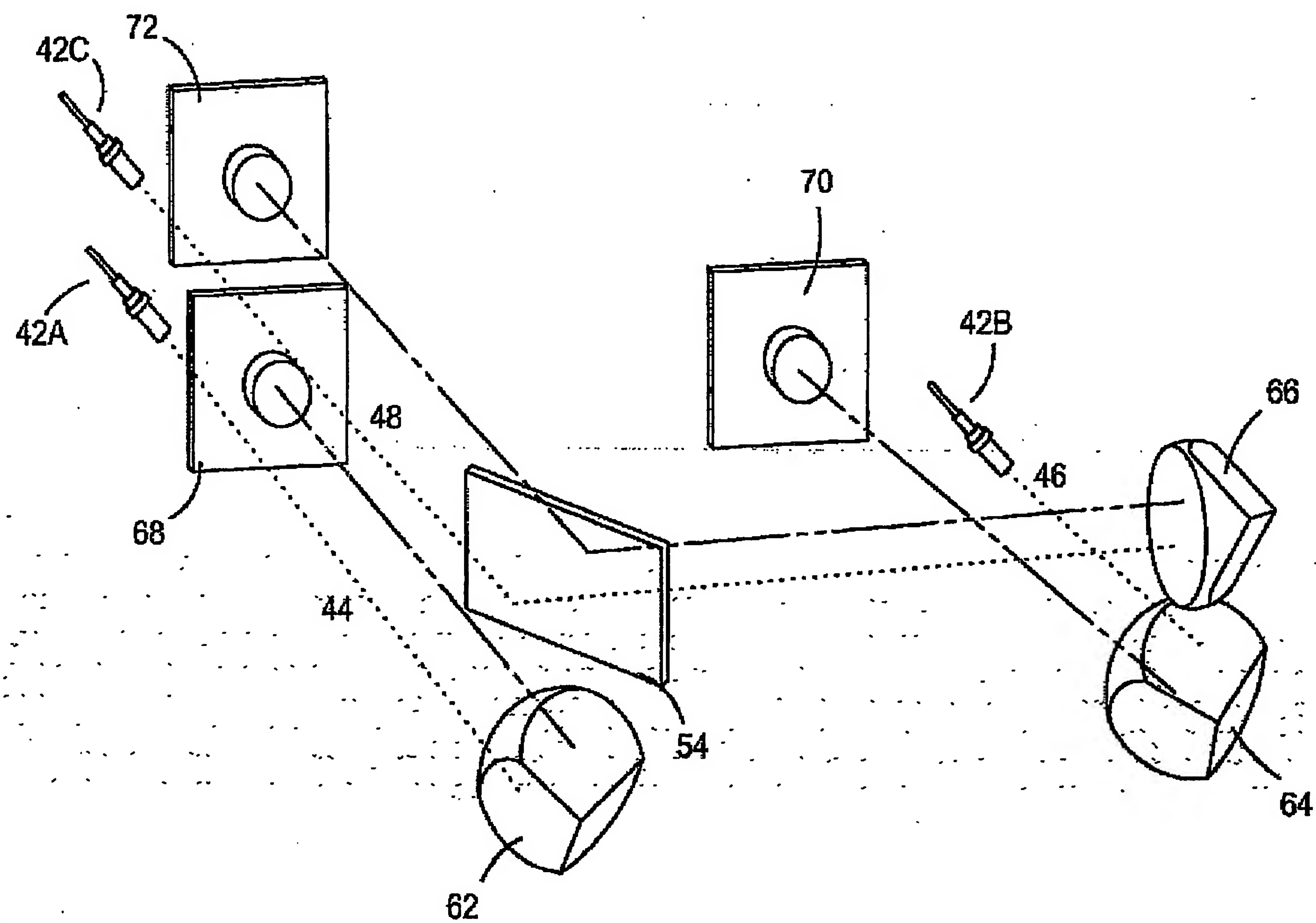

Fig 3

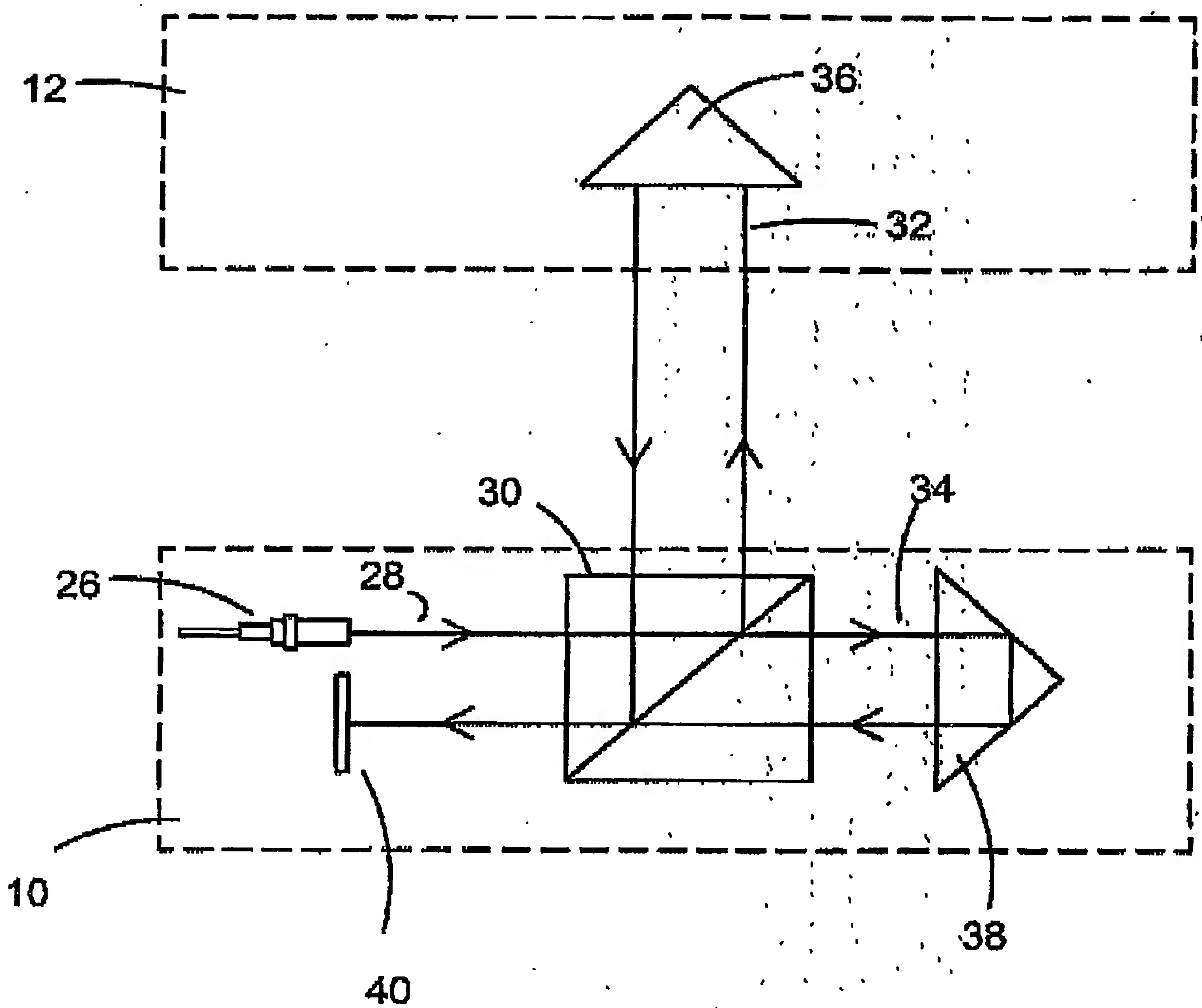

Fig 4

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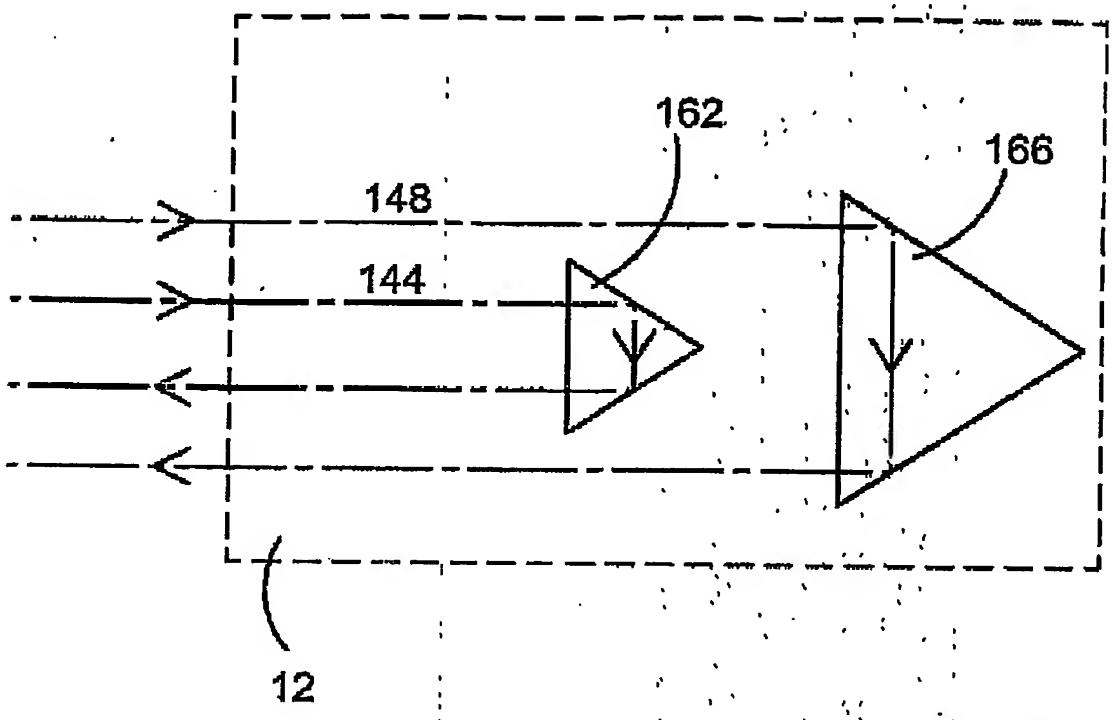

Fig 5

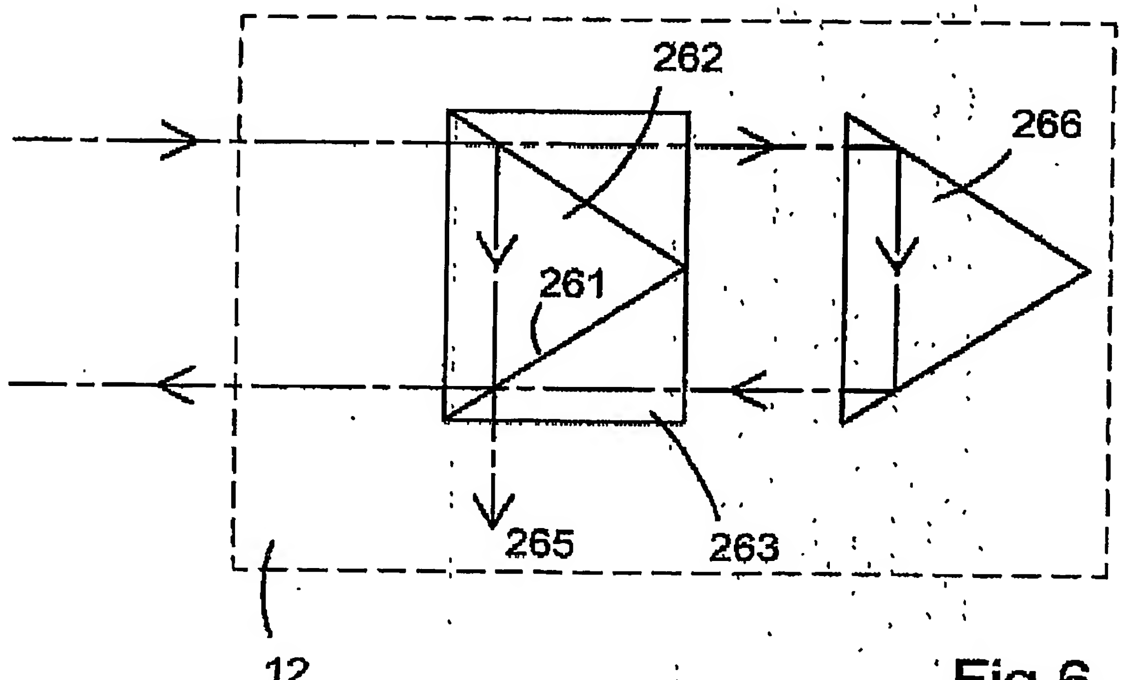

Fig 6

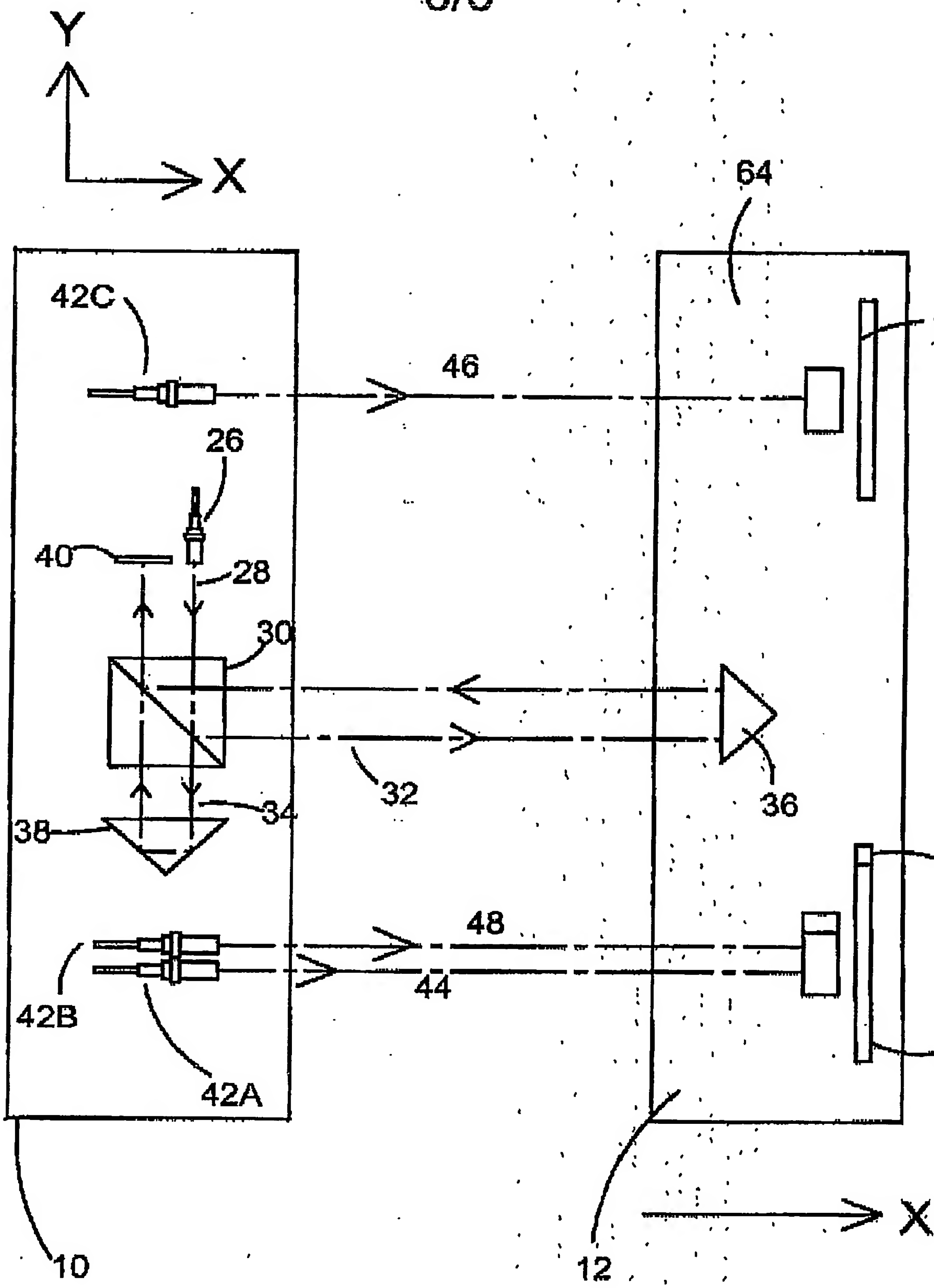

Fig 7

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